

Real-Time PMU-Based Tools for Monitoring Operational Reliability (5.4)

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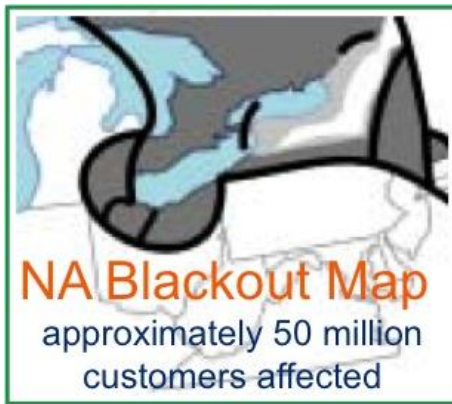
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Context of the Research

2003 North America and 2011 San Diego blackouts

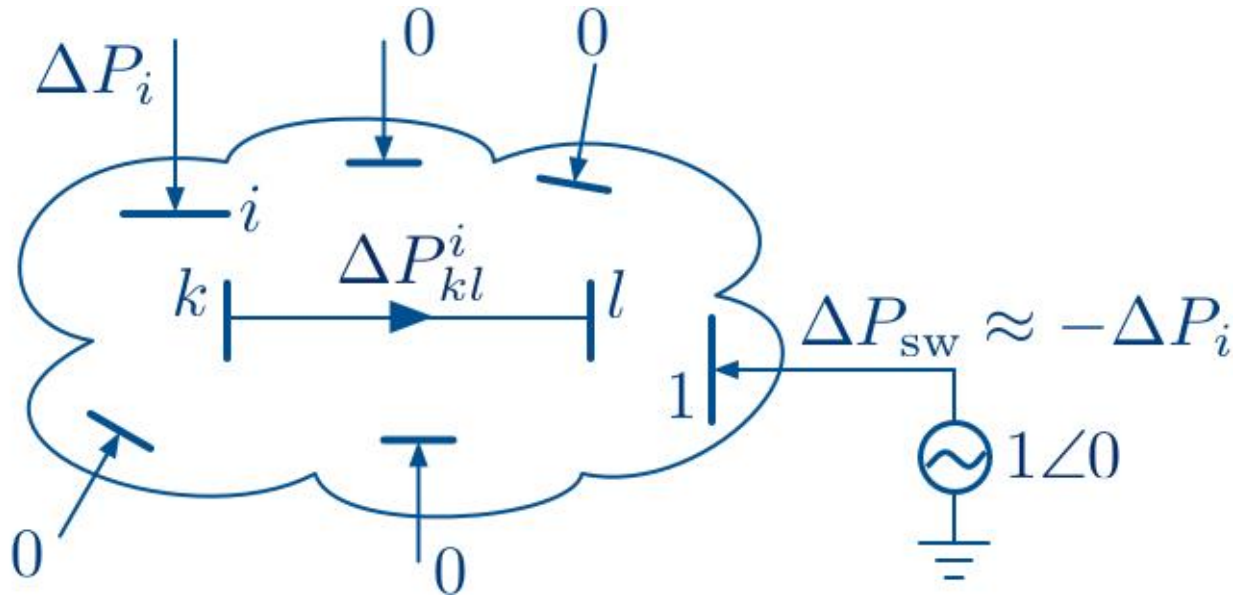


1. Lack of **situational awareness** — limited visibility outside of system
2. Lack of **accurate model** — may not have accurate and timely information about key pieces of system

Research Objective

- Heavy reliance on studies conducted on a model of the system obtained offline based on
 - historical electricity demand patterns
 - equipment maintenance schedules
- Linear sensitivity distribution factors (DFs) are used to help determine whether the system is N-1 secure
Not ideal because
 1. accurate model containing up-to-date network topology is required
 2. results may not be applicable if actual system evolution does not match predicted operating points
- Phasor measurement units (PMUs) provide high-speed voltage and current measurements that are time-synchronized
- **Objective:** Estimate linear sensitivity DFs by exploiting measurements obtained from PMUs without relying on the system power flow model

Injection Shift Factor (ISF)

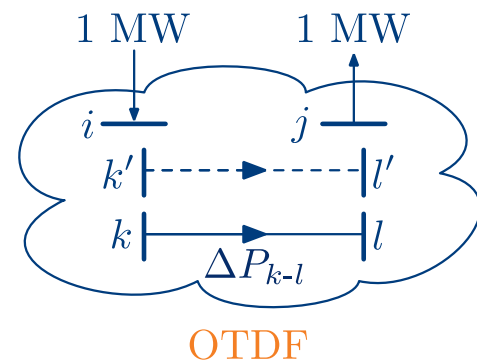
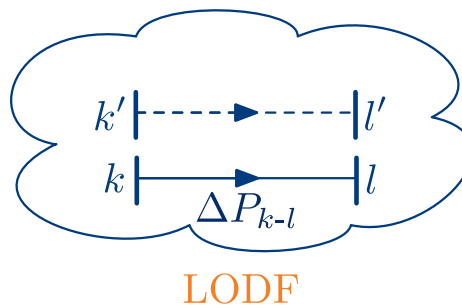
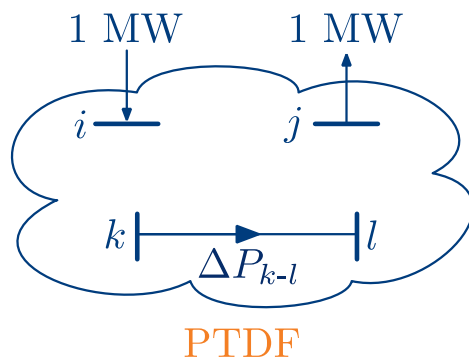


- Ψ_{kl}^i : the ISF of line kl w.r.t. bus i
- **ISF definition:** partial derivative of the real power flow through line kl due to real power injection at bus i w.r.t. to the real power injection at bus i
- Thus, the ISF gives the estimated change in power flow on a transmission line due to a unit change in power injected at a particular bus

$$\Psi_{kl}^i := \frac{\partial P_{kl}}{\partial P_i} \approx \frac{\Delta P_{kl}^i(t)}{\Delta P_i(t)}$$

Other Distribution Factors

- **Power transfer distribution factor (PTDF)** — the MW change in a branch flow for a 1MW exchange between two buses
- **Line outage distribution factor (LODF)** — the MW change in a branch flow due to the outage of a branch with 1MW pre-outage flow
- **Outage transfer distribution factor (OTDF)** — the post-contingency MW change in a branch for a 1MW pre-contingency bus-to-reference exchange



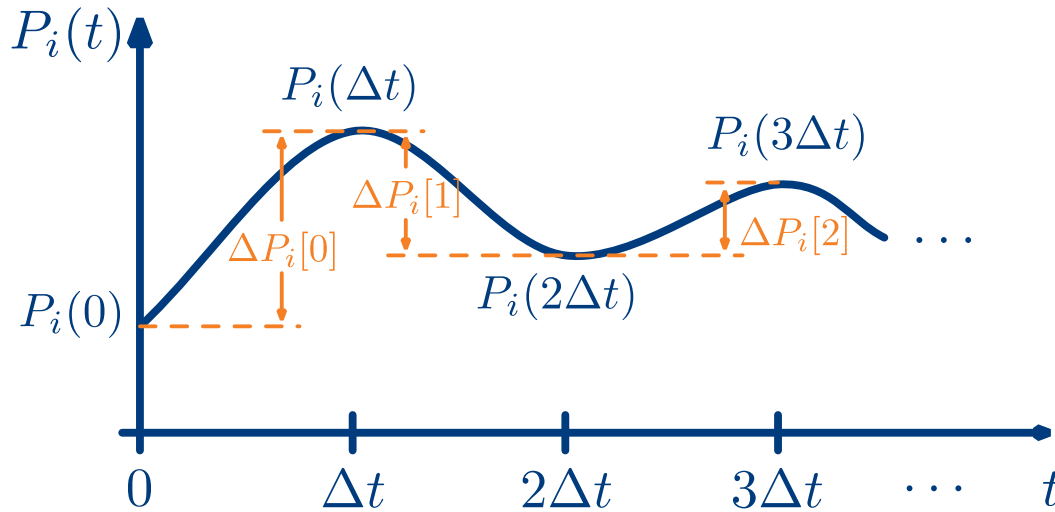
These can all be computed once ISFs are known!

Potential Uses of Research Results

- **Contingency analysis** — establish whether system is N-1 secure based solely on up-to-date measurements
- **Generation and flexible load re-dispatch** — determine optimal re-dispatch policy to avoid contingency without predefined system model
- **Congestion relief** — compute transmission congestion charges with up-to-date DFs obtained in real-time
- **Model validation** — detect model inaccuracy origin by comparing measurement- and model-based results
- **Impact of renewable resource uncertainty on line flows** — deduce the uncertainty in line flows arising from renewable power injection uncertainty

ISF Computation Approach

- Measurements are taken every Δt units of time



$$\Delta P_i(t) = P_i(t + \Delta t) - P_i(t)$$

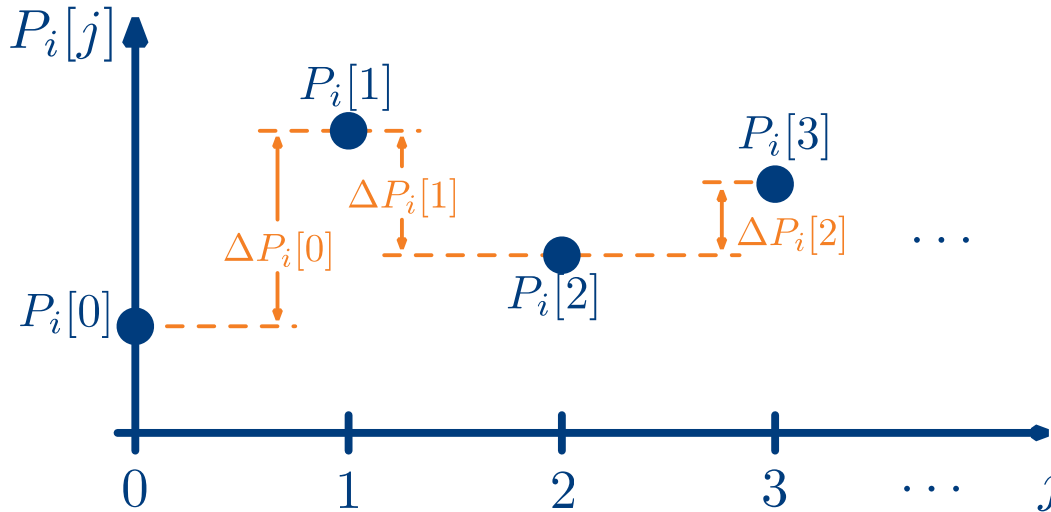
$$\Delta P_{kl}(t) = P_{kl}(t + \Delta t) - P_{kl}(t)$$

- The total change in active power flow in line kl can be approximated as the sum of the change due to the real power injection at each bus by superposition, i.e.,

$$\begin{aligned} \Delta P_{kl}(t) &\approx \Delta P_{kl}^1(t) + \dots + \Delta P_{kl}^i(t) + \dots + \Delta P_{kl}^n(t) \\ &\approx \Delta P_1(t) \Psi_{kl}^1 + \dots + \Delta P_i(t) \Psi_{kl}^i + \dots + \Delta P_n(t) \Psi_{kl}^n \end{aligned}$$

ISF Computation Approach

- Measurements are taken every Δt units of time



Discretize with $t = j\Delta t$

$$\Delta P_i[j] = P_i[j+1] - P_i[j]$$

$$\Delta P_{kl}[j] = P_{kl}[j+1] - P_{kl}[j]$$

- The total change in active power flow in line kl can be approximated as the sum of the change due to the real power injection at each bus by superposition, i.e.,

$$\begin{aligned} \Delta P_{kl}[j] &\approx \Delta P_{kl}^1[j] + \cdots + \Delta P_{kl}^i[j] + \cdots + \Delta P_{kl}^n[j] \\ &\approx \Delta P_1[j]\Psi_{kl}^1 + \cdots + \Delta P_i[j]\Psi_{kl}^i + \cdots + \Delta P_n[j]\Psi_{kl}^n \end{aligned}$$

ISF Computation Approach

- Stacking m of these measurement instances up, where $m > n$, we obtain

$$\underbrace{\begin{bmatrix} \Delta P_{kl}[1] \\ \vdots \\ \Delta P_{kl}[j] \\ \vdots \\ \Delta P_{kl}[m] \end{bmatrix}}_y = \underbrace{\begin{bmatrix} \Delta P_1[1] & \cdots & \Delta P_i[1] & \cdots & \Delta P_n[1] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Delta P_1[j] & \cdots & \Delta P_i[j] & \cdots & \Delta P_n[j] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Delta P_1[m] & \cdots & \Delta P_i[m] & \cdots & \Delta P_n[m] \end{bmatrix}}_H \underbrace{\begin{bmatrix} \Psi_{kl}^1 \\ \vdots \\ \Psi_{kl}^i \\ \vdots \\ \Psi_{kl}^n \end{bmatrix}}_x$$

- An over-determined system of the form $y = Hx$, which we solve via least-squares estimation:

$$\hat{x} = (H^T H)^{-1} H^T y$$

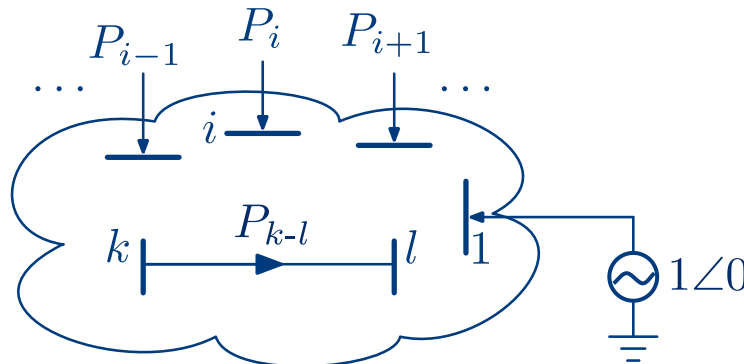
- Method relies on **inherent fluctuations in load and generation**
- Other assumptions
 - The ISFs are approximately constant across the $m+1$ measurements
 - The regressor matrix H has full column rank

Case Study Methodology

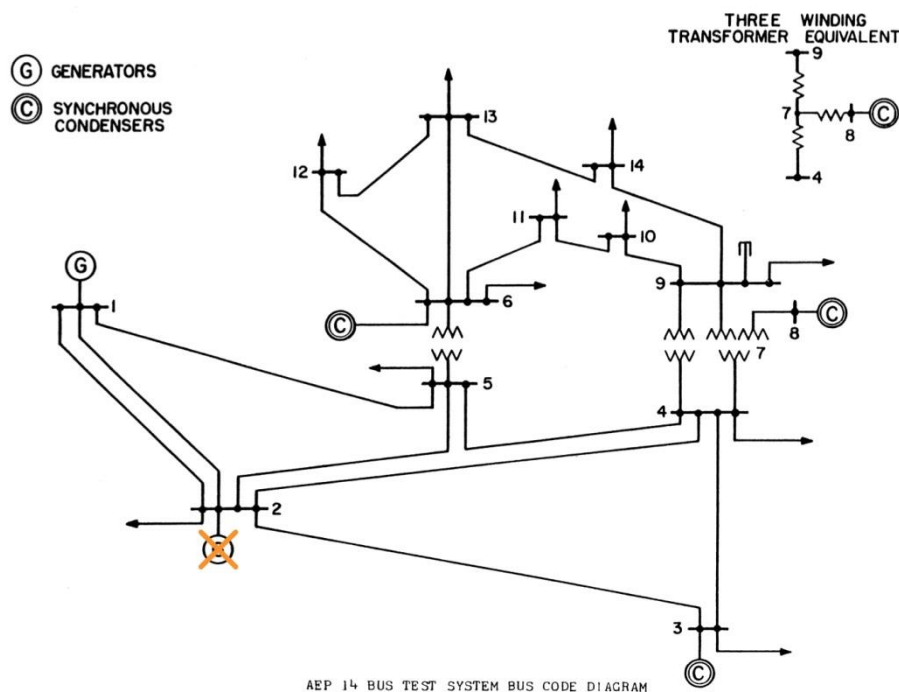
- Simulate PMU measurements of random fluctuations in active power injection at each bus

$$P_i = P_i^0 + \sigma_1 P_i^0 v_1 + \sigma_2 v_2$$

- P_i^0 — nominal power injection at node i
 - v_1 and v_2 — pseudorandom values drawn from standard normal distribution
 - $\sigma_1 P_i^0 v_1$ — inherent variability in power injection with time
 - $\sigma_2 v_2$ — measurement noise
- For each set of random power injection data, compute the power flow, with the slack bus absorbing all power imbalances



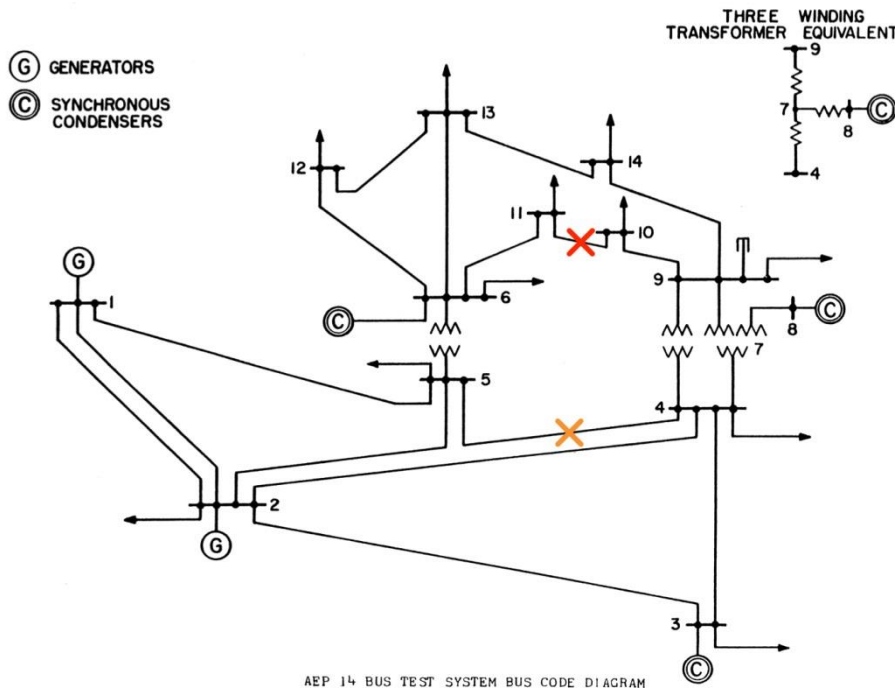
Loss of Generating Unit



- Contingency analysis: what if outage in G_2 occurs?
- G_1 picks up all power imbalance
- Compare ISFs obtained from
 - original system model
 - real-time measurements

Line	Pre-contingency	Post-contingency [p.u.]		
	Actual [p.u.]	Actual	Model-based	LSE
P_{1-2}	1.5674	1.9228	1.9008	1.9226
P_{1-5}	0.7587	0.8281	0.8253	0.8287

Loss of Transmission Line



- Undetected outage in l_{10-11}
- Contingency analysis: what if outage in l_{4-5} occurs?
- Compare LODFs obtained from
 - original system model
 - real-time measurements

Line	Pre-contingency	Post-contingency [p.u.]		
	Actual [p.u.]	Actual	Model-based	LSE
P_{2-3}	0.7295	0.9065	0.8803	0.9052
P_{13-14}	0.0976	0.2116	0.1551	0.2053

Large Test Case Studies

- IEEE 118-bus system divided into internal and external systems
- Case studies with undetected line outages in external system
 1. Generator outage contingency
 - Redistribute lost generation among nearby generators
 - Investigate effect on internal system transmission line flows
 2. Line outage contingency
 - Investigate effect on transmission line flows caused by outage
 3. Generation re-dispatch in constrained system
 - System is not N-1 secure
 - Dispatch out-of-merit generators optimally using ISFs
- In all case studies:
 - Compare results obtained from actual power flow solutions, model-based approach, and proposed measurement-based approach
 - On average, measurement-based approach is more accurate than model-based

Conclusion and Future Work

- Estimate distribution factors
 - using real-time PMU measurements
 - without the use of a mathematical model
- Key advantages
 - Eliminate reliance on system models and corresponding accuracy
 - Resilient to unexpected system topology and operating point changes
 - Opportunity to explore distributed algorithms to solve the problem, using only local PMU data
- Further work
 - Accurate estimate in the presence of corrupted or availability of only a subset of measurements
 - Distributed computation using local information from neighboring nodes
 - Accurate estimate with fewer sets of measurements — would increase responsiveness to system changes